METHODS FOR ESTIMATING GREENHOUSE GAS EMISSIONS FROM MUNICIPAL WASTE DISPOSAL

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DISCLAIMER

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ACKNOWLEDGMENTS

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INTRODUCTION

This chapter covers methane emissions and carbon sequestration from landfilling of solid waste, and greenhouse gas emissions from combustion of solid waste. When waste is landfilled, some of the carbon in the waste is converted to methane (which is emitted to the atmosphere), while some of the carbon remains sequestered in the landfill. When waste is combusted, carbon dioxide and nitrous oxide are emitted.

The purposes of the preferred methods guidelines are to describe emissions estimation techniques for greenhouse gas sources in a clear and unambiguous manner and to provide concise example calculations to aid in the preparation of emission inventories. This chapter describes the procedures and recommended approaches for estimating greenhouse gas emissions from municipal waste management.

Section 2 of this chapter contains a general description of the municipal waste management source category. Section 3 provides a listing of the steps involved in using the preferred method for estimating each type of greenhouse gas emission and sink. Section 4 presents each preferred estimation method; Section 5 provides an alternative estimation technique for landfill methane emissions. Quality assurance and quality control procedures are described in Section 6. References used in developing this chapter are identified in Section 7.

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SOURCE CATEGORY DESCRIPTION

2.1 EMISSION SOURCES

In landfills, methane (CH_4) and carbon dioxide (CO_2) are produced from anaerobic decomposition of organic matter in landfills by methanogenic bacteria. Organic waste first decomposes aerobically (in the presence of oxygen) and is then decomposed by anaerobic non-methanogenic bacteria, which convert organic material to simpler forms like cellulose, amino acids, sugars, and fats. These simple substances are further broken down to gases and short-chain organic compounds (H_2, CO_2, CH_3COOH, $HCOOH$, and CH_3OH), which form the substrates for methanogenic bacteria, which further metabolize these substrates into water and "biogas." The biogas consists of approximately 45 percent CO_2 and 55 percent CH_4 by volume (U.S. EPA 1998a). Additionally, some landfills flare recovered landfill gas, which converts the methane portion of the gas to CO_2.

Neither the CO_2 emitted directly as biogas nor the CO_2 emitted from oxidation of methane at flares is counted as an anthropogenic greenhouse gas emission. The source of the CO_2 is primarily the decomposition of organic materials derived from biomass sources (e.g., crops, forests), and in the U.S. these sources are grown and harvested on a sustainable basis.[1] Sustainable harvests imply that photosynthesis (which removes CO_2 from the atmosphere) is equal to decomposition (which adds CO_2 to the atmosphere), and thus CO_2 emissions from biogas or CH_4 oxidation are not counted in GHG inventories.

Much of the carbon in landfills that is not converted to CO_2 or CH_4 is stored indefinitely and removed from the pool of carbon available to cycle to the atmosphere, i.e., it is sequestered. In accordance with IPCC's convention on GHG accounting, only biogenic carbon (i.e., carbon from plant or animal matter) is counted as sequestered. Plastics that are landfilled represent a transfer of carbon from one long-term carbon pool (oil or natural gas reserves) to another (landfills), and thus are not counted as incremental carbon sequestered.

In waste combustors, both CO_2 and nitrous oxide (N_2O) are emitted. CO_2 is produced from oxidation of organic materials in waste, such as paper, food scraps, yard trimmings, and plastic. As with CO_2 from biogas and oxidation of CH_4, CO_2 emissions from biogenic sources (e.g., paper and food scraps) are not counted as a greenhouse gas, because they simply return CO_2 that plants recently absorbed through photosynthesis to the atmosphere. However, some CO_2 is from nonbiogenic sources (e.g., plastic and rubber made from petroleum), and is thus counted as a greenhouse gas. Nitrous oxide is produced at the high temperature found in waste combustors by

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[1] The Intergovernmental Panel on Climate Change's (IPCC) convention also calls for counting emissions from biogenic sources when they are harvested on a non-sustainable basis. In the U.S., paper, wood, and food are the primary biogenic sources of waste-related CO_2 emissions; these are all harvested on a sustainable basis.

the combination of nitrogen (both nitrogen contained in the waste and nitrogen gas in the air) and oxygen gas in the air.

2.2   FACTORS INFLUENCING LANDFILL GAS EMISSIONS

Numerous factors affect the amount of CH_4 and CO_2 produced in landfills. The factors may be divided into two general categories: management practices and physical factors.

Management Practices	Physical Factors
Portion of Waste That is Landfilled Density of Refuse Particle Size of Refuse	Waste Composition Moisture Content of Waste Nutrient Availability Landfill Temperature Leachate pH

Municipal solid waste (MSW) constitutes a significant portion of both the waste produced in the United States and the waste deposited in landfills.[2] The two types of waste management practices that lead to methane production are open dumping and sanitary landfilling. Since the amount of waste that is openly dumped in the United States is negligible (and CH_4 production from open dumping, or waste piles, is highly uncertain and based on anecdotal evidence) CH_4 emissions from open dumping are assumed to be zero.

In sanitary landfills (termed "landfills" in this chapter), a tightly packed, anaerobic environment favorable for landfill gas production is created as compacted waste is spread over the active area of the landfill and is covered with soil (as well as a low-permeability cover at final closure).

Other variables of management practices that affect CH_4 generation are density and particle size of refuse. One way to increase density is by shredding refuse. Shredding not only increases density, but also reduces particle size, which results in a greater surface area exposed to bacterial activity, moisture, and nutrients. In addition, if shredded refuse is spread evenly in thin layers (about 12 inches) and then compacted, the volume of waste is further reduced. As density increases, the degree of saturation (*i.e.*, the ability to absorb water) will increase due to greater mass, which can lead to more gas production per unit volume (Pacey and DeGier, 1986). Extremely dense refuse (*i.e.*, baled refuse), however, can be relatively impermeable to water, and consequently, may produce less gas (Pacey and DeGier, 1986). Other variables that may affect emissions are the design and size of the landfill and the use of cover soils and membrane covers. The composition of municipal solid waste affects the amount of landfill gas produced. Municipal solid waste supplies the necessary starting material for methane generation in landfills

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[2] Other types of waste that may produce methane in landfills are hazardous and industrial solid waste, and agricultural waste. Hazardous and industrial waste landfills may contain compounds that are directly or indirectly toxic to methanogenic bacteria (an example of indirect toxicity is creation of a low- or high-pH environment). Agricultural waste, if landfilled, could potentially be a significant source of methane emissions but is typically not deposited where anaerobic conditions develop (see Bingemer and Crutzen, 1987).

by providing degradable organic carbon (DOC), which is metabolized by methanogenic bacteria to produce landfill gas.[3] Food waste has a high DOC content, as do some grades of paper (e.g., office paper); wastes such as metal and glass have no DOC.

Another physical factor influencing landfill gas production is the moisture content of the landfill environment (Pacey and DeGier, 1986). Moisture is essential to anaerobic decomposition and the life of methanogenic bacteria. Water serves as a transport medium for nutrients, bacteria, and alkaline substances within the refuse (Pacey and DeGier, 1986). As the moisture level increases, bacteria become more active and multiply, increasing methane production. The moisture of the refuse can be determined by analyzing the composition of the landfilled MSW and determining the percentage of "wet refuse" (e.g., food wastes) and "dry refuse" (e.g., paper waste). Unfortunately, no reliable functional relationship exists between moisture content of the landfill environment and gas production estimates (Emcon Associates, 1982).[4] As more of the landfill capacity in the U.S. employs highly engineered liner, cover, and leachate collection systems, the moisture content of landfilled waste is going down over time. Developing a better understanding of the relationship between moisture content and gas production is an important research need.

Other factors that are important but have not been factored into any emission estimate, due to the lack of data, include the leachate pH and nutrient availability. The optimal pH for gas production is near neutral, between 6.8 and 7.2; this pH range is not usually reached for several years (Pacey and DeGier, 1986). Methane generation is not inhibited unless the environment is very acidic (pH <6.0). Alkaline substances, dissolved in water, help to balance the pH level and neutralize organic acids, which in large concentrations decrease methane production.

Temperature, unlike leachate pH, can be related to the amount of degradable organic carbon that will generate landfill gas (*i.e.*, the fraction of DOC dissimilated). At temperatures below 50-59° F, methane production is drastically reduced (Pacey and DeGier, 1986). Because the majority of methane production occurs in the deeper layers of the landfill, where heat is generated from anaerobic decomposition, temperatures typically range between 77-104° F. An average of 95° F can be expected within the anaerobic zone (below 6.5-13 ft.) (Gunnerson and Stuckey, 1986, cited in Bingemer and Crutzen, 1987) and will result in about 77 percent dissimilated DOC.[5] At

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[3] DOC is biochemically decomposed to form substrates and can be divided into two parts: dissimilated and assimilated. The dissimilated fraction is the portion of carbon in substrates that is converted to landfill gas (i.e., CO_2 and CH_4), and the assimilated fraction is the remainder of carbon that is used to produce new microbial cell material (Tabasaran, 1981).

[4] In a study conducted by EPA, a correlation between landfill gas generation rate and precipitation rate was obtained (no correlation between precipitation rate and moisture content in the landfill was evaluated). Based on data from 12 "wet" landfills (annual precipitation of 1.9 ft. or more) and data from 8 "dry" landfills (precipitation of less than 1.9 ft.), landfill gas emissions from "wet" landfills were about 2.6 times greater than emissions from "dry" landfills (Thorneloe, 1990).

[5] Landfill temperature is related to the amount of DOC that is dissimilated to produce biogas by the relationship: $C_C / C_T = (0.014\ T + 0.28)$, where C_C = carbon converted to biogas, C_T = total carbon compounds in substrates, and T = landfill temperature (Tabasaran, 1981). From this relationship, as temperature increases, so does the rate of gas formation.

extremely high temperatures (above 140º F) methane generation usually ceases (Pacey and DeGier, 1986).

2.3 LANDFILL GAS CONTROL TECHNIQUES

Landfill gas recovery can be an important factor in reducing CH_4 emissions from landfills, as well as provide a source of renewable energy. Due to a U.S. EPA rule that requires gas recovery at large MSW landfills, the number of landfill gas recovery systems is increasing and the CH_4 generated from landfills is being captured and flared or used as an energy source.[6] States should estimate the amount of CH_4 in recovered landfill gas in order to subtract it from total CH_4 generated by landfills. This has been accounted for in the methodology presented, although each state will need to estimate the quantity of CH_4 captured from landfill gas recovery sites.

2.4 FACTORS INFLUENCING LANDFILL CARBON SEQUESTRATION

Some carbon compounds, such as cellulose, degrade readily in a landfill. Others, such as lignin, are resistant to decomposition in a landfill. Different types of waste contain different proportions of the various compounds. For example, lignin (produced by trees) is a major component of newspaper, but is a minor component of office paper. This is because in the papermaking process, lignin is removed from pulp used to make finer grades of paper such as office paper. The amount of carbon sequestered in a landfill depends largely on the amount of stable biogenic carbon compounds, such as lignin, in the waste that is landfilled.

2.5 FACTORS INFLUENCING WASTE COMBUSTION GHG EMISSIONS

The amount of nonbiogenic CO_2 emitted when waste is combusted depends on the amount of nonbiogenic carbon in the waste, and the percentage of nonbiogenic carbon that is oxidized. The amount of N_2O emitted when waste is combusted depends on the temperature of the combustion chambers and the amount of nitrogen in the waste.

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[6] The rule requires a well-designed and well-operated landfill gas collection system at landfills that (1) have a design capacity of at least 2.5 million metric tons and 2.5 million cubic meters, and (2) emit more than 50 metric tons of nonmethane organic compounds per year (Federal Register, Vol. 63, p. 32743, June 16, 1998).

3

OVERVIEW OF AVAILABLE METHODS

This chapter presents methods for estimating emissions from municipal solid waste disposal. Disposal is a subset of integrated municipal waste management. Integrated waste management covers a broad spectrum of activities that are generally categorized as source reduction, recycling (including composting), combustion, and landfilling. Source reduction, which reduces the quantity of materials produced and subsequently disposed, results in no waste-related GHG emissions. GHG emissions from recycling and composting are confined to GHG emissions from facility operations and transportation. This chapter discusses emissions from waste disposal through combustion and landfilling, the only two waste-related sources of emissions addressed in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (1997).*[7]

Methods for developing greenhouse gas inventories are continuously evolving and improving. The methods presented in this volume represent the work of the EIIP Greenhouse Gas Committee in 1998 and early 1999. This volume takes into account the guidance and information available at the time on inventory methods, specifically, U.S. EPA's *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions* (U.S.EPA 1998a), volumes 1-3 of the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 1997), and the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 1996* (U.S. EPA 1998b)

There have been several recent developments in inventory methodologies, including:

- Publication of EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 1997* (U.S. EPA 1999) and completion of the draft inventory for 1990 – 1998. These documents will include methodological improvements for several sources and present the U.S. methodologies in a more transparent manner than in previous inventories;

- Initiation of several new programs with industry, which provide new data and information that can be applied to current methods or applied to more accurate and reliable methods (so called "higher tier methods" by IPCC); and

- The IPCC Greenhouse Gas Inventory Program's upcoming report on Good Practice in Inventory Management, which develops good practice guidance for the implementation of the 1996 IPCC Guidelines. The report will be published by the IPCC in May 2000.

Note that the EIIP Greenhouse Gas Committee has not incorporated these developments into this version of the volume. Given the rapid pace of change in the area of greenhouse gas inventory methodologies, users of this document are encouraged to seek the most up-to-date information from EPA and the IPCC when developing inventories. EPA intends to provide periodic updates to the EIIP chapters to reflect important methodological developments. To determine whether an updated version of this chapter is available, please check the EIIP site at http://www.epa.gov/ttn/chief/eiip/techrep.htm#green.

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[7] A life-cycle approach to estimating emissions from municipal waste management is also possible, although this is not the approach outlined in the IPCC Guidelines or the U.S. Inventory. Please refer to the EPA/OSW report entitled *Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste* (U.S. EPA 1998d). This report can be found on the Internet at www.epa.gov/owswer/non-hw/muncpl/ghg.htm.

3.1 OVERVIEW OF PREFERRED METHOD FOR ESTIMATING LANDFILL METHANE EMISSIONS

Because it is generally impractical to measure methane emissions from each of the hundreds of landfills in individual states, efforts to estimate emissions from landfills use one of two alternatives:

- Determine the emissions "potential" of a representative quantity of refuse through theoretical considerations (*e.g*., carbon content) or laboratory simulation. Scale this value to the state level by estimating the quantity of refuse in landfills statewide.

- Use available data to determine the actual generation rates of methane per unit of refuse and multiply this value by the estimated quantity of refuse disposed of in landfills statewide.

The first approach has been the most frequently used method to estimate emissions from landfills. It relies on kinetic models of landfill gas formation or on simulations conducted in laboratories. This method assumes conditions that occur in kinetic models or under laboratory conditions closely simulate actual field conditions. This assumption limits the accuracy of the method, because it is difficult to determine whether theoretical or laboratory conditions actually simulate field conditions. The second approach, which relies on field measurements, is the preferred method of analysis because it relies on field data rather than theoretical results.

The approach suggested for the calculations below is based on an emissions model developed for the report *Anthropogenic Methane Emissions in the U.S.: Report to Congress* (U.S. EPA 1993). This method, which is used by EPA in preparing the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1997* (hereafter, the "U.S. Inventory") (EPA 1999), uses a statistical model derived initially from analyses performed by the U.S. EPA Air and Energy Engineering Research Laboratory (AEERL) and enhanced by the U.S. EPA Office of Air and Radiation (OAR). Emissions estimates may be calculated by collecting various state-level data, and applying this information to the method. The method presented consists of the following ten steps:

> **Step 1:** Obtain the required data.
> **Step 2:** Estimate waste in place at MSW landfills.
> **Step 3:** Estimate fraction of waste in large versus small MSW landfills.
> **Step 4:** Classify the state as arid or non-arid.
> **Step 5:** Estimate methane generated from waste in place at small MSW landfills.
> **Step 6:** Estimate methane generated from waste in place at large MSW landfills.
> **Step 7:** Estimate total methane generated from MSW landfills.
> **Step 8:** Estimate methane generated from industrial landfills.
> **Step 9:** Adjust for flaring and recovery.
> **Step 10:** Adjust for oxidation.
> **Step 11:** Convert to metric tons of carbon equivalent (MTCE).

The emissions model on which this method is based was developed by examining and confirming data from 85 landfills that recover methane gas to produce energy. The data analyzed in detail the relationships between methane recovery and (1) refuse quantity; (2) refuse character-istics (e.g., moisture content, temperature, and pH); and (3) landfill characteristics (such as age, depth, volume, and surface area).[8] The analysis showed that a simple model using the total amount of waste in place and the landfill's location in an arid or non-arid climate was adequate for estimating methane production. Because this method is based on the total waste in place at a landfill, and not on annual waste generation and disposal rates, it accounts for timed releases of methane instead of assuming that all of the methane generated is released in a single year.

The analysis indicated that the amount of methane gas generated per unit of waste was higher in landfills with over 1.1 million tons of waste in place than landfills with less than 1.1 million tons of waste in place. To account for this, a separate model was developed to calculate emissions from landfills with less than 1.1 million tons of waste in place.[9] In summary, the emissions depend on three key factors: (1) total waste in place; (2) landfill size; and (3) location in an arid or non-arid climate.

Because the models only determine the amount of gas *generated* by the landfill, the results of the model must be adjusted to determine actual *emissions*.[10] As previously described, some of the methane produced by landfills is recovered to produce energy, flared to meet environmental and safety requirements, or oxidized in the soils covering the landfill.

In sum, methane emissions to the atmosphere may be estimated based on methane production from municipal landfills, methane produced by industrial landfills, methane flared or recovered, and methane oxidized in landfills before being released to the atmosphere. These adjustments can be described as:

Net Methane Emissions =   municipal landfill methane generation
                              plus   industrial landfill methane generation
                              minus   municipal landfill methane flaring or recovery
                              minus   industrial landfill methane flaring or recovery
                              minus   methane *oxidation* by soil.

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[8] Please note that the analysis assumes that landfill wastes produce methane over a thirty year period. If the actual period is significantly longer, the emissions may be slightly understated.

[9] The accuracy range of the equations for large landfills (±15%) is better than for small landfills (±20%) because the estimate for large landfills is based on a greater number of actual landfill methane production measurements. In addition, please note that the equations provided for small and large landfills were developed using statistical models to establish the relationship between the quantity of waste in place and methane produced in small and large landfills. The estimates yielded by the models are not congruent at their boundary conditions (1.1 million tons of waste in place).

[10] It should be noted that the analysis used to create the model is based on data describing the methane *recovered* from landfills. The methane recovery information is an imperfect surrogate for methane generation. If the landfills used in this analysis are not representative of landfills as a whole, then the models used in this analysis may not accurately represent state landfill methane generation.

Municipal solid waste (MSW) landfills are estimated to account for over 90 percent of all methane emissions from landfills in the U.S. (EPA 1993). Industrial landfills, which receive nonhazardous waste from factories, processing plants, and other manufacturing activities, account for the remainder of landfill methane emissions.

3.2 OVERVIEW OF ALTERNATIVE METHODS FOR ESTIMATING LANDFILL METHANE EMISSIONS

Two alternative methods for estimating landfill methane emissions are presented in section 5. The first method, described in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (1997), is relatively simple to use; it employs a simple equation and data for which data sources are readily available. This model assumes that all methane is emitted during the year in which it is disposed, and will yield very inaccurate estimates if waste disposal rates are changing over time. The second method is more complex; it involves estimating methane generation over time, based on a theoretical first-order kinetic model. This model, known as the Landfill Air Emissions Estimation Model, was developed by EPA to estimate landfill gas generation; it has been cross-checked against methane emission estimates generated by other estimation methods.

3.3 OVERVIEW OF PREFERRED METHOD FOR ESTIMATING LANDFILL CARBON SEQUESTRATION

The preferred method for estimating landfill carbon sequestration involves determining the amount of waste landfilled in the state during the inventory year, and multiplying that amount by a carbon sequestration factor. The method uses easily obtained data, and applies to municipal landfills only. Unlike the landfill methane methodology, which is used for the U.S. National Inventory of GHG Emissions, this method has not yet been applied for the U.S. Inventory,[11] nor is it the subject of IPCC guidance.

3.4 OVERVIEW OF PREFERRED METHOD FOR ESTIMATING WASTE COMBUSTION GREENHOUSE GAS EMISSIONS

The preferred method for estimating waste combustion greenhouse gas emissions involves determining the amount of waste combusted in the state during the inventory year, and multiplying that amount by (1) a CO_2 emission factor and (2) an N_2O emission factor. The method uses easily obtained data. N_2O emissions from waste combustion are explicitly included in the U.S. Inventory; CO_2 emissions from waste combustion are addressed in the context of energy emissions, as part of the non-fuel uses of fossil energy.

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[11] The US Inventory includes an estimate of carbon sequestered in landfills based on an analysis of carbon flows in wood products.

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PREFERRED METHODS FOR ESTIMATING EMISSIONS

This section presents the preferred methodologies for estimating methane emissions from landfills, and for estimating CO_2 and N_2O emissions from waste combustion. The landfill methane methodology consists of eleven steps, presented in section 4.1. The methodology for estimating landfill carbon sequestration is presented in section 4.2. The waste combustion GHG methodology consists of three steps, as presented in section 4.3.

4.1 PREFERRED LANDFILL METHANE METHODOLOGY

Step (1) Obtain Required Data

- *Required Data.* The following information is needed to estimate methane emissions from landfills.

  (1)   **Waste in place in the state.** For the purposes of this estimation methodology, waste in place is defined as the total quantity of waste that has been landfilled over the previous thirty years.

  (2)   **Fraction of waste in place in large versus small MSW landfills.** Large landfills are defined here as those that have a total of more than 1.1 million tons of waste in place.

  (3)   **The state's average annual rainfall.**

  (4)   **Quantity of landfill methane that is recovered for energy purposes or flared.**

- *Data Sources.* The following data sources may be used.

  (1)   Waste in place in the state. State solid waste offices or other state agencies may track the amount of waste deposited into landfills; if so, waste in place may be estimated from this information. If a state does not have information on the quantity of waste in place, waste in place may be estimated based on the state's current population, and the current national average annual amount of waste landfilled per person. For waste in place at industrial landfills, formulas shown in Step 8 (below) may be used if state information is not available.

If a state does not have waste in place data for landfills in the state, data may be obtained from EPA's Methane Energy Branch. EPA has published working drafts of 31 state landfill profiles entitled *Landfill Gas-to-Energy Opportunities: Landfill Profiles for the State of [State]*. Landfill profiles for states listed in Table 5.4-1 can be downloaded from the EPA Landfill Methane Outreach Program (LMOP) internet site at http://www.epa.gov/lmop. State profiles include data for landfills in each state with greater than 1 million tons of waste in place.

(2)   **Fraction of waste in place in large versus small MSW landfills.** The fraction of total waste placed in large and small landfills over the past 30 years may be available from the state solid waste office; if not, it may be estimated using default values shown in Step 3 (below).

(3)   **The state's average annual rainfall.** A state is considered arid if average rainfall is less than 25 inches per year. A table provided later in this section lists those states that receive, on average, less than 25 inches of rainfall per year (the arid states). All other states are considered to be nonarid.

(4)   **Quantity of landfill methane that is recovered for energy purposes or flared.** Information on landfill methane flaring and recovery may be available from state solid waste offices. If a state does not have data on landfill methane recovery, these data may be obtained from EPA's Landfill Gas Recovery database, which reports on all US landfill gas to energy projects.[12] Currently, EPA does not have a state database of flaring estimates, but is developing one in conjunction with the Solid Waste Association of North America (SWANA). Older data can be found in Berenyi, E., and R. Gould, "*1994-1995 Methane Recovery from Landfill Yearbook*," Government Advisory Associates (GAA), Inc., 1994.

Table 5.4-1   Available State Landfill Profiles

Alabama	Iowa	Nebraska	Pennsylvania
California	Kansas	Nevada	Tennessee
Colorado	Kentucky	New Jersey	Texas
Connecticut	Louisiana	New York	Utah
Florida	Maryland	North Carolina	Virginia
Georgia	Massachusetts	Ohio	Washington
Illinois	Minnesota	Oklahoma	Wisconsin
Indiana	Missouri	Oregon	

- *Units for Reporting Data.* Waste in place should be reported in tons of mixed solid waste per year. The amount of landfill methane flared or recovered for energy purposes should be reported in tons of methane per year.

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[12] This database is available from the US EPA Climate Protection Division at 202-564-9190.

Step (2) Estimate Waste in Place at MSW Landfills

- If state data are available on the total quantity of waste that has been landfilled over the previous thirty years, these data should be used.

- If state data are not available on the total quantity of waste that has been landfilled over the previous thirty years, the waste in place may be estimated by using the following formula:

  Waste in Place (tons) = Current State Population × Current Per Capita Waste Landfilling Rate (lbs/capita/yr) × "30-Year Multiplier for Waste in Place" ÷ 2,000 lbs/ton

  Where:
  > *Per Capita Waste Landfilled Rate in 1995* is about 902 lbs./person/year (2.47 lbs./person/day)—substitute state-specific values if available.

  > *30-Year Multiplier for Waste in Place* is as defined below (with values presented in Table 5.4-3).

<u>30-Year Multiplier for Waste in Place</u>

In most states, the quantity of waste that is landfilled each year is much larger now than it was 30 years ago. This is due to both an increase in population and an increase in the annual amount of waste landfilled per person. Changes in the national average annual amount of waste landfilled per person are shown in the final column of Table 5.4-2. As the table shows, this value peaked around 1980; since then, recycling and source reduction efforts have reduced the waste landfilling rate. Nonetheless, the total amount of waste landfilled per year is higher now than it was 30 years ago. Thus, using the current annual amount of waste landfilled as a proxy for the annual amount landfilled over the past thirty years would likely overestimate the total waste in place.

Table 5.4-2: Amount of Waste Per Capita in the U.S.

Year	Daily Amount Generated (lbs./person/day)	Daily Amount Landfilled (lbs./person/day)	Annual Amount Landfilled (lbs./person/year)
1960	2.68	1.69	617
1965*	2.97	2.03	741
1970	3.25	2.36	861
1975*	3.46	2.67	975
1980	3.66	2.98	1088
1985*	4.00	2.94	1073
1990	4.33	2.89	1055
1995	4.34	2.47	902
* Interpolated values Source: EPA (1997).			

In order to account for changes in the annual amount of waste landfilled, a multiplier is used. In the U.S., waste produces methane for about thirty years, so a 30-year multiplier must be estimated. The appropriate multiplier depends on the average amount of time that waste produces methane, and on the rate of population growth and the amount of waste landfilled per capita over this period. EPA estimated a set of multipliers to account for varying population growth rates in different states. EPA first estimated, for a hypothetical state, the amount of waste that would have been landfilled over the previous 30 years, for various population growth rates, under an assumption that the state's annual amount landfilled per capita has followed the general national trend as shown in Table 5.4-2. EPA then calculated, for the hypothetical state, the amount of waste landfilled in the past year, assuming the per capita landfilling rate was the same as the national rate. The 30-year multiplier is the ratio of the first value to the second value. Appropriate multipliers are provided in Table 5.4-3. For example, Table 5.4-3 shows that a state with an average population growth rate of 2 percent would have a 30-year multiplier of 24.8 for the 1965-1995 period.

Table 5.4-3: 30-Year Multiplier for Waste in Place[a]

Average Annual Population Growth for Period	1%	2%	3%	4%	5%	6%	7%
Equivalent Ratio of (Population at End of Period)/(Population at Start of Period)	1.3	1.8	2.4	3.2	4.3	5.7	7.6
30-Year Multiplier for Waste in Place for the Period 1960-1990	23.1	20.4	18.2	16.3	14.7	13.4	12.3
30-Year Multiplier for Waste in Place for the Period 1965-1995	28.3	24.8	22.0	19.6	17.6	15.9	14.5
[a] Assuming that waste produces methane for 30 years.							

Example   Waste in place for a state that had a 1995 population of 8 million, and an average annual population growth of 2 percent since 1965, would be calculated as follows:

Waste in Place   =   8 million people × 902 lbs/person/year × 24.8 ÷ 2,000 lbs./ton

                  =   89 million tons waste in place.

Step (3) Estimate Fraction of Waste in Place in Large Versus Small MSW Landfills

Once the total quantity of waste in place has been estimated, the next step is to estimate the fraction of total waste in place in large versus small landfills. For this estimation methodology, a large landfill is defined as having more than 1.1 million tons of waste in place.

- Some states may have information on the fraction of waste disposed in large landfills. If this information is not available, then the fraction may be estimated using default values shown in Table 5.4-4.

Table 5.4-4: Default Values for the Fraction of Waste in Large Versus Small Landfills

Region	States Located in Region	Fraction of Waste Landfilled at Large Landfills
Northeast	Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Ohio, Pennsylvania, Rhode Island, Vermont	89%
Southeast	Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Virginia, West Virginia	73%
Midwest	Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, Oklahoma, North Dakota, South Dakota, Texas, Wisconsin	81%
West	Alaska, Arizona, California, Colorado, Hawaii, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, Wyoming	86%
Source: Derived from EPA (1988).		

Example   Assume that total landfilled waste for a state is 90 million tons, of which 20 percent is in small landfills and 80 percent is in large landfills. Therefore, the amount of waste in place in small and large landfills is simply:

Waste in place at small landfills: 20% $\times$ (90 million tons) = 18 million tons

Waste in place at large landfills: 80% $\times$ (90 million tons) = 72 million tons

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Step (4) Classify State as Nonarid or Arid

Moisture is an important factor in the production of methane in landfills. Landfills in nonarid climates are believed to produce more methane per unit of waste in place than do landfills in arid climates.

- Different methane emission estimates have been developed for nonarid states and for arid states. Table 5.4-5 lists those states that are classified as arid states -- i.e., states that have average rainfall of less than 25 inches per year. All other states are considered to be nonarid states.

- If a state has distinct arid and non-arid areas, then the additional steps described at the end of Steps 5 and 6 should be used.

Table 5.4-5: Arid States (States with average annual rainfall less than 25 inches)

Arizona	Montana	North Dakota
California	Nebraska	South Dakota
Colorado	Nevada	Utah
Idaho	New Mexico	Wyoming
Source: Department of Commerce (1988)		

Step (5) Estimate Methane Generated from Waste in Place at Small MSW Landfills

- The following equations are used to estimate the range of methane generated from small landfills based on the quantity of waste in place. The equations below should be used for nonarid and arid states, respectively. The equations estimate methane emissions in cubic feet per ton of waste in place per day.

    Nonarid: Methane (ft^3/day) = 0.35 W (tons) +/- 20%

    Arid: Methane (ft^3/day) = 0.27 W (tons) +/- 20%

    where W = Waste in place (tons)

- To convert this result for daily methane emissions in ft^3 to annual methane emissions in tons, multiply the result by 0.0077. This factor is derived from the following calculation:

$$\frac{365 \text{ (days/year)} \times 19.2 \text{ (g/ft}^3)}{453.49 \text{ (g/lb.)} \times 2,000 \text{ (lb./ton)}} = 0.0077 \frac{\text{(ton CH}_4\text{/year)}}{\text{(ft}^3\text{/day)}}$$

Example   Methane generated at small landfills for a *nonarid* state with 18 million tons of waste in place at small landfills would be estimated as follows:

Small landfills: 18 million tons $\times$ 0.35 (ft^3/ton/day) =   6.3 million ft^3/day

= 6.3 million ft^3/day $\times$ 0.0077 $\dfrac{\text{(tons CH}_4\text{/yr)}}{\text{(ft}^3\text{/day)}}$

= 49,000 tons CH_4/yr

- If a state is partially arid, then a weighted average based on the percentage of waste disposed in arid regions may be used to estimate the methane generated from small land-fills. If the amount of waste in small landfills in arid and non-arid regions is known, then both equations above may be used, using the appropriate value for "W" in each equation.

Step (6) Estimate Methane Generated from Waste in Place at Large MSW Landfills

- The method for estimating the range of methane emissions from large landfills is slightly more complex than the method for estimating the range of emissions from small landfills.[13] The additional steps are (1) estimate the total number of large landfills in the state and (2) divide total waste in place at large landfills by the total number of large landfills to obtain average waste in place at large landfills. The number of large landfills and the average waste in place at these landfills are then used in the equations below to estimate methane generated. The equations below should be used to estimate methane generated for nonarid states and arid states, respectively.

$$\text{Nonarid: Methane (ft}^3/\text{day)} = N \times [417,957 + 0.26\ W_{avg}\ \text{(tons)}]$$

$$\text{Arid: Methane (ft}^3/\text{day)} = N \times [417,957 + 0.16\ W_{avg}\ \text{(tons)}]$$

Where $N =$ Number of large landfills in the state
$W_{avg} =$ Average waste in place (tons) at large landfills

Example   Methane generated for an *arid* state that has five large landfills and waste in place at large landfills of 72 million tons would be estimated as follows:

1. Estimate average waste in place at large landfills

   $W_{avg} =$ 72 million tons/5 landfills = 14.4 million tons/landfill

2. Estimate methane generated at large landfills

   $CH_4 (\text{ft}^3\ CH_4/\text{day}) = 5 \times [417,957 + (0.16 \times 14,400,000)] =$ 13.6 million ft^3 CH$_4$/day

   13.6 million ft^3 CH$_4$/day $\times$ 0.0077 $\dfrac{\text{(tons CH}_4/\text{yr)}}{\text{(ft}^3\ CH_4/\text{day})}$ = 104,000 tons CH$_4$/yr

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- To convert to methane generated in tons per year multiply the result by 0.0077.

- If a state is partially arid, then a weighted average based on the percentage of waste disposed in arid regions may be used to estimate the methane generated from large land-fills. If the amount of landfilled waste in arid and non-arid regions is known, then both of the above equations may be used, using the appropriate value for "W" in each equation.

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[13] The accuracy range of the equations for large landfills (±15 percent) is better than for small landfills (±20 percent) because the estimate for large landfills is based on a greater number of actual landfill methane production measurements.

- A more accurate, but slightly more complex, method for estimating methane emissions from large landfills may be used when state data are available on the quantity of waste in place at each large landfill in the state. If these data are available, the following equations for nonarid states and for arid states may be used. These equations are slightly modified versions of those equations presented above.

$$\text{Nonarid: Methane (ft}^3 / \text{day)} = \left(\sum_{i=1}^{n} [417,957 + .26w_i] \right) \pm 15\%$$

$$\text{Arid: Methane(ft}^3 / \text{day)} = \left(\sum_{i=1}^{n} [417,957 + .16w_i] \right) \pm 15\%$$

Where n = number of large landfills in the state
w_i = waste in place (tons) at each landfill

Step (7) Estimate Total Methane Generated from MSW Landfills

- Total methane generated from MSW landfills is the sum of methane generated at small landfills (Step 5) and methane generated at large landfills (Step 6).

Step (8) Estimate Methane Generated from Industrial Landfills

Methane is also generated from waste deposited in non-hazardous industrial landfills. Although methane generation from non-hazardous industrial landfills is believed to be small relative to that from MSW landfills, industrial landfill methane generation is still a significant source of methane emissions. Note that methane generation from industrial landfills does not include methane generation from industrial waste disposed of into MSW landfills. This methane generation is already accounted for under MSW landfills.

- The quantity of waste in industrial landfills and its methane generation rate usually must be estimated, because data are generally not available. Based on estimates of the quantity of waste in place at industrial landfills and on the estimated organic content of industrial landfills compared to MSW landfills, EPA (1993) estimated that methane generation from industrial landfills in the U.S. is approximately 7% of methane generation from MSW landfills in the U.S. This 7% value may be used to estimate state methane generation from industrial landfills.

- Alternatively, if state information is available on the quantity of waste in place (WIP) at industrial landfills, the ratio of emissions from industrial landfills to emissions from MSW landfills may be calculated as follows, based on organic content percentages reported in EPA (1993):

$$\frac{\text{Average 11\% organic content} \times \text{WIP at Industrial Landfills}}{\text{Average 69\% organic content} \times \text{WIP at MSW Landfills}} = \text{Ratio of emissions from Industrial Landfills to Emissions from MSW Landfills (\%)}$$

The resulting value would be used in place of the 7 percent default value.

- Total methane generation then equals MSW methane generation (Step 7) plus industrial landfill methane generation.

Example   For a state that has an estimated 108,000 tons of methane generated from large MSW landfills and 49,000 tons from small MSW landfills, methane emissions from industrial waste landfills would be calculated as follows:

7% $\times$ (108,000 tons CH$_4$+ 49,000 tons CH$_4$) = 11,000 tons CH$_4$

Total methane generated would be: 157,000 tons CH$_4$ from MSW landfills
                                             + 11,000 tons CH$_4$ from industrial landfills
                                             = 168,000 tons CH$_4$

Step (9) Adjust for Flaring and Recovery

- Some states have landfills that either flare some of the methane that is produced or recover the methane and use it as an energy source. Estimates of recovered methane from landfill gas to energy projects for the states listed in Table 5.4-1 can be obtained from the EPA Landfill Methane Outreach Program profiles mentioned in 'Step One.' For states not profiled by EPA, refer to the GAA publication mentioned in "Step (1)." For estimates of the amount of landfill gas flared, data may be available from directly contacting landfill operators or should be estimated on the basis of flaring equipment capacity. Methane that is flared or recovered should be subtracted from total methane generated (as estimated in Step 8).

Preliminary Net Methane Emissions	=	Total Methane Generated	-	Methane Flared or Recovered

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Example   For a state that has a total landfill methane generation of 168,000 tons per year and recovers or flares 10,000 tons of landfill CH$_4$ per year, the methane generated (minus the amount flared or recovered) would be calculated as follows:

168,000 tons CH$_4$ generated - 10,000 tons CH$_4$ recovered or flared = 158,000 tons CH$_4$

Step (10) Adjust for Oxidation

Methane may be oxidized in the top layer of soil over the landfill. Regardless of whether a landfill gas recovery system is in place, methane not collected by a recovery system will pass upward through the landfill cover or surrounding soils, where it may be oxidized (Whalen, Reeburgh and Sandbeck, 1990). The amount of oxidation that occurs is uncertain and depends on latitude (affecting surface soil temperature), soil characteristics, and other factors. Currently, there is limited research available to assist in quantifying the amount of methane that is oxidized during this process. Four papers published in 1997 address this question (Kjeldsen, Dalager and Broholm, 1997, Bogner, Spokas and Burton, 1997, Liptay, et al. 1997, and Bogner, Meadows,

and Czepiel, 1997). EPA assumes that 10 percent of the methane generated that is not flared or recovered is oxidized in the soil. Accordingly, methane generated (minus the amount flared or recovered) (Step 9) should be multiplied by 90 percent to account for oxidation.[14]

- Once the adjustment for oxidation has been made, the result is total methane emissions from landfills.

| Total Methane Emissions from Landfills | = | Preliminary Net Methane Emissions | $\times$ | 0.90 |

Example   Total methane emitted to the atmosphere from landfills for a state with total methane generated (minus amount flared or recovered) of 158,000 tons would be calculated as follows:

Total methane emissions: 158,000 tons CH_4 generated $\times$ 90% not oxidized = 142,000 tons CH_4

Step (11) Convert to Metric Tons of Carbon Equivalent

- Perform the calculation shown below to convert the emissions to units of metric tons of carbon equivalent. These calculations convert (1) tons to metric tons, and (2) metric tons of gas to metric tons of carbon equivalent (by multiplying the mass ratio of carbon to carbon dioxide, and by the global warming potential). The global warming potential (GWP) for methane is 21.

Example   Emissions of CH_4 from landfills are converted to metric tons of carbon equivalent (MTCE) as follows:

CH_4 Emissions: 142,000 tons $CH_4 \times$ 0.907 metric tons/ton $\times$ (12/44) $\times$ 21 = **553,200 MTCE**

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[14] Where state-specific oxidation rates are available, use 1 minus the oxidation rate in place of the 90 percent default value presented here.

4.2   PREFERRED METHODOLOGY FOR ESTIMATING LANDFILL CARBON SEQUESTRATION

The method for estimating carbon sequestration from landfilling is being developed by the U.S. EPA Office of Solid Waste as part of its research on the relationship between solid waste management and GHG emissions and sinks (U.S. EPA 1998c). While the methodology has been reviewed several times (most recently by the EIIP greenhouse gas committee), it has not yet been adopted for the US inventory and there is not a corresponding IPCC method.

One of the elements of the EPA/OSW methodology is a landfill carbon sequestration factor (i.e., the amount of carbon sequestered per ton of mixed municipal solid waste landfilled). This factor is based on laboratory studies (Barlaz 1997) in which mixed municipal waste was dried, analyzed for cellulose, hemicellulose, and lignin content, weighed, placed in two-liter plastic containers (i.e., reactors), and allowed to decompose anaerobically under warm, moist conditions designed to accelerate decomposition. The reactors were seeded with a small amount of well-decomposed refuse containing an active population of microorganisms. The reactors were allowed to run until either no more gas was produced or an extrapolation of prior gas emissions indicated that the reactors had emitted 95 percent of the gas that would ultimately be emitted if allowed to run forever. At the end of the experiment, the contents of the reactors were dried, weighed, and analyzed for cellulose, hemicellulose, and lignin content. From these data, the amount of carbon remaining undecomposed was estimated.

The results of the experiment showed that when mixed municipal waste is landfilled, approximately 0.18 tons of carbon are sequestered for each ton of waste landfilled. These findings are broadly consistent with recent research by the U.S. Department of Agriculture, Forest Service (Skog, 1998), which has indicated that there is considerable sequestration of carbon when wood and various types of paper are landfilled.

Note that the sequestration rate used here represents the residual amount of carbon storage after decomposition is complete (which may take 30 years or longer). In reality, carbon storage is highest immediately after the waste is deposited, and then declines over time due to the action of decomposition and leaching. Rather than expressing sequestration as a time-varying rate, this method uses the simplifying approach of attributing long-term carbon sequestration in the year in which waste is deposited.

Step (1) Obtain Required Data

- *Required Data*. The information needed to estimate carbon sequestration from landfilling of municipal solid waste (i.e., waste from residential and commercial sources) is the amount of MSW landfilled in the state during the inventory year, in short tons.

- *Data Sources*. If in-state data sources provide the information needed, those sources should be used. If not, information on the amount of waste landfilled may be calculated

using an annual survey of municipal waste management practices published each spring by *Biocycle* magazine (published by The JG Press in Emmaus, Pennsylvania, typically in its April edition) and an annual EPA report entitled "*Characterization of Municipal Solid Waste in the United States: 1997 Update*" (U.S. EPA 1998b). Although the *Biocycle* survey presents figures for waste management practices by state, these figures include industrial and construction and demolition waste disposed at municipal solid waste facilities. The samples of "mixed municipal solid waste landfilled" used in the laboratory studies mentioned above probably resemble a mix of wastes more similar to those addressed in the EPA *Characterization Report* than the mix reported by *Biocycle*. Therefore, it is necessary to scale the *Biocycle* estimates using the EPA *Characterization Report* estimate of municipal solid waste landfilled in the U.S.

In order to estimate MSW landfilled in the state using these two sources, 1) multiply the *Biocycle* estimate of waste landfilled in the state by 2) the ratio of (a) the EPA estimate of MSW landfilled to (b) the *Biocycle* estimate of waste landfilled in the U.S.

Step (2) Estimate Carbon Sequestration from Landfilling of Municipal Waste

- Multiply the tonnage of MSW landfilled by a factor of 0.18 tons of carbon sequestered per ton of MSW landfilled.

$$\text{Carbon Sequestration from MSW Landfilled (tons)} = \text{MSW Landfilled (tons)} \ \mathbf{x} \ 0.18 \text{ tons carbon sequestered/ton of MSW landfilled}$$

Example According to Biocycle's 1998 Survey, the amount of waste landfilled in Pennsylvania in 1997 was 5 million tons, as compared to a total of 208 million tons landfilled in the U.S. (Biocycle 1998). According to EPA's *Characterization Report*, 116 million tons of MSW were landfilled in the U.S. (U.S. EPA 1998b). The amount of MSW landfilled in Pennsylvania in 1997 can be calculated as follows:

5 million tons landfilled in PA $\times$ (116 million tons MSW landfilled in U.S./ 208 million tons landfilled in U.S.) = 3 million tons MSW landfilled in PA

Carbon sequestration from landfilling of waste in Pennsylvania in 1997 can be calculated as follows:

3 million tons MSW landfilled $\times$ 0.18 tons carbon sequestered/ton MSW landfilled
=   0.5 million tons carbon sequestered

Step (3) Convert to Metric Tons of Carbon Equivalent

- Finally, to convert from units of short tons of carbon to metric tons of carbon, multiply the result of step 2 by 0.907 MT per ton.

Note that landfill carbon sequestration represents a sink (in effect, a negative emission); the results from this approach carry a negative sign when summing across sources of GHGs.

4.3 PREFERRED METHODOLOGY FOR ESTIMATING GREENHOUSE GAS EMISSIONS FROM WASTE COMBUSTION

EPA's work on solid waste and GHG emissions also provides a basis for estimating the CO_2 and N_2O emissions from municipal waste combustion (U.S. EPA 1998d). To develop this estimate of CO_2 emissions, the first step was to estimate the amount of nonbiogenic carbon in municipal waste. Three waste categories contain non-biogenic carbon: plastics, textiles, and a combined category for rubber and leather (U.S. EPA 1997). EPA used simplifying assumptions that (1) all carbon in textiles is non-biomass carbon, i.e., petrochemical-based plastic fibers such as polyester, and (2) the category of rubber and leather is composed almost entirely of rubber. Based on these assumptions, EPA estimated that there are 0.11 tons of non-biogenic carbon in the plastic, textiles, rubber, and leather contained in one ton of mixed municipal waste. EPA estimated that 98 percent of this carbon would be converted to CO_2 when the waste was combusted, with the balance going to the ash. The resulting estimate of CO_2 emissions from waste combustion slightly overstates the emissions, because not all textiles are made of petrochemical-based fibers. However, the magnitude of the error is small because textiles represent only a small fraction of the MSW stream.

Recent studies compiled by the Intergovernmental Panel on Climate Change (IPCC 1996) show that MSW combustion results in measurable emissions of N_2O. The IPCC compiled reported ranges of N_2O emissions, per metric ton of waste combusted, from six classifications of MSW combustors. EPA estimated the average emissions from waste combustion by averaging the midpoints of each range (U.S. EPA 1998d).[15]

Step (1) Obtain Required Data

- *Required Data.* The information needed to estimate emissions of N_2O and nonbiogenic CO_2 from combusted municipal solid waste (MSW) is the amount of MSW combusted annually in the state, in short tons.

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[15] In addition, many waste combustors in the US produce electricity, thus displacing electricity generated from fossil fuels and reducing electric utility GHG emissions. For the purposes of conducting a GHG inventory, however, these utility GHG reductions are already reflected in the inventory of fossil fuel GHG emissions. Similarly, many US waste combustors recover scrap steel from the combustor ash; when this steel is recycled there are energy savings (and GHG reductions) compared to manufacturing the same amount of steel from virgin inputs. Again, for GHG inventory purposes, these GHG impacts need not be counted in the waste combustion analysis because they are already reflected in the inventory of fossil fuel and industrial sector GHG emissions.

- *Data Sources*. If in-state data sources provide the information needed, those sources should be used. If not, the quantity of MSW combusted in the state may be calculated using an annual survey of municipal waste management practices published each spring by *Biocycle* magazine (published by The JG Press in Emmaus, Pennsylvania, typically in its April edition) and an annual EPA report entitled "*Characterization of Municipal Solid Waste in the United States: 1997 Update*" (U.S. EPA 1998b). Although the *Biocycle* survey presents figures for waste management practices by state, these figures include industrial and construction and demolition waste disposed at municipal solid waste facilities. As mentioned in the previous section, the mix of wastes used for the laboratory studies estimating carbon sequestration probably resemble a mix of wastes more similar to those addressed in the EPA *Characterization Report* than the mix reported by *Biocycle*. Therefore, in order to remain consistent with the emission estimates generated in Section 9.4.2, it is necessary to scale the *Biocycle* estimates using the EPA *Characterization Report* estimate for municipal solid waste combusted in the U.S.

  In order to estimate MSW combusted in the state using these two sources, 1) multiply the *Biocycle* estimate of waste combusted in the state (note that Biocycle generally refers to waste incineration rather than waste combustion) by 2) the ratio of (a) the EPA estimate of MSW combusted to (b) the *Biocycle* estimate of waste combusted in the U.S.

Step (2) Estimate CO_2 Emissions from Combustion of Municipal Waste

- Multiply the tonnage of MSW combusted by 0.40 tons of non-biogenic CO_2 per ton of MSW combusted (U.S. EPA 1998d).

Nonbiogenic CO_2 Emissions   =   MSW Combusted (tons)   **x**   0.40 tons CO_2/ton of MSW
from MSW Combusted (tons)   combusted

Example According to Biocycle's 1998 Survey, the amount of waste combusted in Pennsylvania in 1997 was 2 million tons, as compared to a total of 31 million tons combusted in the U.S. (Biocycle 1998). According to EPA's *Characterization Report*, 36 million tons of MSW were combusted in the U.S. (U.S. EPA 1998b). The amount of MSW combusted in Pennsylvania in 1997 can be calculated as follows:

2 million tons combusted in PA × (36 million tons MSW combusted in U.S./ 31 million tons combusted in U.S.) = 2.3 million tons MSW combusted in PA

Nonbiogenic CO_2 emissions from combustion of waste in Pennsylvania in 1998 can be calculated as follows:

2.3 million tons MSW combusted × 0.40 tons CO_2/ton MSW combusted
= **1 million ton CO_2**

Step (3) Estimate N$_2$O Emissions from Municipal Waste

- Multiply the tonnage of MSW combusted by 0.0001 tons of N$_2$O emitted per ton of MSW combusted.

N$_2$O Emissions from Combustion of Municipal Waste (tons)	=	MSW combusted (tons)	**x**	0.0001 tons of N$_2$O/ton of MSW combusted

Example	Total N$_2$O emissions from combustion of waste in Pennsylvania in 1997 can be calculated as follows:
	2.3 million tons $\times$ (0.0001 tons of N$_2$O/ton MSW combusted) = **230 tons N$_2$O**

Step (3) Convert to Metric Tons of Carbon Equivalent

- Perform the calculations shown below to convert the emissions to units of metric tons of carbon equivalent. These calculations convert (1) tons to metric tons, and (2) metric tons of gas to metric tons of carbon equivalent (by multiplying the mass ratio of carbon to carbon dioxide, and by the global warming potential for each gas). The global warming potential (GWP) for nitrous oxide is 310.

Example	Emissions of N$_2$O from combustion are converted to metric tons of carbon equivalent (MTCE) as follows:
	230 tons N$_2$O $\times$ .907 metric ton/ton $\times$ (12/44) $\times$ 310 = **18,000 MTCE**

5

ALTERNATE METHODS FOR ESTIMATING EMISSIONS

This section presents two alternative methods for estimating methane emissions from landfills if states are not able to obtain the data required to use the recommended method.

5.1 ESTIMATING LANDFILL CH$_4$ EMISSIONS ASSUMING INSTANTANEOUS EMISSIONS

The simplest methodology for estimating CH$_4$ emissions from landfills is based on a mass balance approach, where an instantaneous release of methane is assumed to enter the atmosphere during the same year that refuse is placed in the landfill (Bingemer and Crutzen 1987). This approach is used in the *Revised 1996 IPCC Guidelines* as the default methodology for estimating methane emissions from solid waste disposal sites. Bingemer and Crutzen divided the world into four economic regions: U.S./Canada/Australia, Other OECD, USSR/Eastern Europe, and Developing Countries. Then they determine how much MSW is produced for each region and how much of that MSW is degradable organic carbon. To calculate the annual emissions from MSW, Bingemer and Crutzen used the following equation:

(1) Methane Emissions = Total MSW generated (lbs./yr) $\times$
MSW landfilled (%) $\times$
DOC in MSW (%) $\times$
Fraction Dissimilated DOC (%) $\times$
0.5 lbs. CH$_4$/lb biogas $\times$
Conversion factor (16 lbs. CH$_4$/12 lb. C) –
Recovered CH$_4$ (lbs./yr)

Note that the first two factors in the equation above may be obtained from individual state EPA Solid Waste Divisions. The following default values for North America may be used for the third and fourth factors in the equation above:

- DOC in MSW = 18-21 percent (IPCC 1996)
- Fraction Dissimilated = 77 percent (IPCC 1996, Bingemer and Crutzen 1987). Recent discussions among IPCC experts indicate that the current default value for fraction dissimilated may be too high.

The revised IPCC guidelines add a factor to Bingemer and Crutzen's equation to adjust for oxidation of landfill methane. However, the default value for the oxidation factor is currently set at zero, pending the availability of further data (IPCC 1996). In the U.S., it would be acceptable

to complete the equation above and follow the methodology presented in Section 4.1, "Step (10) Adjust for Oxidation."

5.2 ESTIMATING LANDFILL CH$_4$ EMISSIONS BASED ON A FIRST-ORDER KINETIC MODEL

A more complex method for estimating methane emissions from landfills is based on a first-order kinetic model of methane production which considers timed releases of methane to the atmosphere (U.S. EPA 1998a,). EPA's Landfill Air Emissions Estimation Model (LAEEM), a modified version of the Scholl Canyon model, is described in detail in *1998 Compilation of Air Pollutant Emission Factors, AP-42* (U.S. EPA 1998a). LAEEM is also available through the Office of Air Quality Planning and Standards (OPAPS) Technology Transfer Network Website (OAQPS TTN Web) in the Clearinghouse for Inventories and Emission Factors (CHIEF) technical area (URL http://www.epa.gov/ttn/chief).

LAEEM is most effective when applied to individual landfills, but it may also be applied at the state level. Estimates have also been made for the U.S. using this model or its precursors (e.g., Colt et al., 1990). The model assumes that gas production will be highest upon initial placement of waste in the landfill (after a certain negligible lag period during which anaerobic conditions are formed). The rate then decreases exponentially (i.e., undergoes first-order decay) as the availability of degradable organic carbon decreases (U.S. EPA, 1990). The model equation and variables are described briefly below:

$$Q_{CH4} = L_O \times R \times (e^{-kc} - e^{-kt})$$

where, Q_{CH4} = methane generation rate at year t (ft^3/yr),
  L_O = methane generation potential (ft^3/ton of refuse),
  R = average annual refuse acceptance rate during active life (tons/yr),
  k = methane generation rate constant (yr^{-1}),
  c = time since closure (c = 0 for active landfills) (yr), and
  t = time since initial refuse placement (yr).

Site-specific landfill information must be supplied for variables R, c, and t. In cases where refuse acceptance rates are unknown, R can be estimated by dividing waste in place by the years the landfill was actively accepting waste. If it is necessary to calculate R, note that the waste deposited in landfill cells that exclusively accept nondegradable refuse (e.g., concrete, brick, stone, glass, plaster, wallboard, piping, plastics, and metal objects) need not be included in the estimate of waste in place.

At specific landfills, the methane generation potential, L_0, varies as a function of the moisture and organic content of the refuse. The methane generation constant, k, is a function of several factors, including moisture, pH, temperature, and other factors (U.S. EPA 1998a). This constant determines how quickly the methane generation rate decreases. The default values shown below represent the best fit for 21 landfills. Note, however, that predicted methane emissions ranged

from 38 to 492 percent of actual emissions, so there is considerable variability among landfills, and considerable uncertainty in this (and the other) estimation methods.

Table 5.5-1. Data Elements and Corresponding Sources

Data Element Needed	Default Values	Source of Data
L_0	3,530 ft^3/ton	U.S. EPA 1998a
R	-	Landfill owner
k	0.04/yr if $\geq$ 25 inches of rain 0.02/yr if $<$ 25 inches of rain	U.S. EPA 1998a
t	-	Landfill owner
c	-	Landfill owner

6

QUALITY ASSURANCE/QUALITY CONTROL

Quality assurance (QA) and quality control (QC) are essential elements in producing high quality emission estimates and should be included in all methods to estimate emissions. QA/QC of emissions estimates are accomplished through a set of procedures that ensure the quality and reliability of data collection and processing. These procedures include the use of appropriate emission estimation methods, reasonable assumptions, data reliability checks, and accuracy/logic checks of calculations. Volume VI of this series, *Quality Assurance Procedures*, describes methods and tools for performing these procedures.

There are several uncertainties associated with using the recommended method for estimating methane emissions from landfills. First, the actual number and size of landfills and other waste management facilities are not known with certainty. Many small and unregulated facilities may exist that are not included in these estimates. Second, the time period over which landfilled waste produces methane also is not certain. At present, the assumed time period is thirty years. This could be an overestimate or underestimate. Third, this methodology is based on information from methane recovered from various landfills. These landfills may not be representative of landfills as a whole. Fourth, little information is available on the amount of methane oxidized during diffusion through the soil cover over landfills. The assumed ten percent is based on limited measurements. Finally, the method of estimating methane emissions from small landfills is less accurate than the one for large landfills. This difference is due to the fact that more methane measurements were taken from large landfills than small ones. The basis for estimating emissions from small landfills needs to be improved. Other sources of uncertainty in estimating CH_4 emissions from landfills are the effects of climate on methane emission rates, the impact of landfill design characteristics and maintenance procedures (Piccot et al., 1990), the methane generation potential of industrial wastes compared to municipal wastes, and the effect of landfill gas recovery systems on the anaerobic zone in landfills (active pumping may draw more air into the fill, thus inhibiting methanogenesis).

The rate of carbon sequestration in landfills is even more uncertain than landfill methane emissions. The rate depends on several factors, including the amount of stable biogenic carbon compounds, such as lignin, in the landfilled waste, availability of moisture and nutrients, landfill design characteristics, and many of the other factors related to decomposition of organics. There is very little empirical data on the fraction of wastes that is sequestered.

Both CO_2 and N_2O are emitted from waste combustion. Nonbiogenic CO_2 emissions from waste combustion depend on the amount of nonbiogenic carbon in the waste, and the percentage of nonbiogenic carbon that is oxidized. The amount of N_2O emitted when waste is combusted depends on the temperature of the combustion chambers and the amount of nitrogen in the waste. There are two main limitations associated with the recommended method for estimating GHG

emissions from waste combustion. First, for CO_2 emissions, EPA used simplifying assumptions that (1) all carbon in textiles is non-biomass carbon, i.e., petrochemical-based plastic fibers such as polyester, and (2) the category of rubber and leather is composed almost entirely of rubber. The resulting estimate of CO_2 emissions from waste combustion slightly overstates the emissions. Second for N_2O emissions, the reported ranges for N_2O emissions were broad; in some cases the high end of the range was ten times the low end of the range. Research has indicated that N_2O emissions vary with the type of waste burned.

6.1   DATA ATTRIBUTE RANKING SYSTEM (DARS) SCORES

DARS is a system for evaluating the quality of data used in an emission inventory. To develop a DARS score, one must evaluate the reliability of eight components of the emissions estimate. Four of the components are related to the activity level (e.g., the amount of waste landfilled). The other four components are related to the emission factor (e.g., the amount of methane emitted per unit of waste landfilled). For both the activity level and the emission factor, the four attributes evaluated are the measurement method, source specificity, spatial congruity, and temporal congruity. Each component is scored on a scale of zero to one, where one represents a high level of reliability. To derive the DARS score for a given estimation method, the activity level score is multiplied by the emission factor score for each of the four attributes, and the resulting products are averaged. The highest possible DARS composite score is one. A complete discussion of DARS may be found in Chapter 4 of Volume VI, *Quality Assurance Procedures*.

The DARS scores provided here are based on the use of the emission factors provided in this chapter, and activity data from the sources referenced in the various steps of the methodology. If a state uses state data sources for activity data, the state may wish to develop a DARS score based on the use of state data.

TABLE 5.6-1

DARS SCORES: CH$_4$ EMISSIONS FROM LANDFILLS

DARS Attribute Category	Emission Factor Attribute	Explanation	Activity Data Attribute	Explanation	Emission Score
Measurement	3	The factors are derived from a model which in turn draws from a limited set of measurements.	6	If a state uses the Workbook formula for waste in place, the activity level is estimated based on state and national data.	0.18
Source Specificity	10	The emission factors were developed specifically for landfills.	7	The activity data are highly correlated to the emissions process.	0.70
Spatial Congruity	5	Emission factors were developed for arid and non-arid regions; but even within these regions, spatial variability is probably moderate to high.	7	If a state uses the EIIP formula for waste in place, the national average per capita waste landfilled is used instead of state-specific data; spatial variability is expected to be moderate.	0.35
Temporal Congruity	8	The emission factor is based on a model that estimates average annual emissions over a 30-year time frame. Temporal variability is expected to be low.	8	If a state uses the EIIP formula for waste in place, the state's current population and population growth rate is used to estimate waste placed over the past 30 years.	0.64
				Composite Score	**0.47**

TABLE 5.6-2

DARS SCORES: LANDFILL CARBON SEQUESTRATION

DARS Attribute Category	Emission Factor Attribute	Explanation	Activity Data Attribute	Explanation	Emission Score
Measurement	5	The sequestration factor is based on laboratory research data.	10	The amount of waste combusted is measured by weighing garbage trucks before and after they tip their waste at the combustor.	0.50
Source Specificity	6	The sequestration factor was developed for a subset of the source category; expected variability is moderate.	7	The activity data are highly correlated to the sequestration process.	0.42
Spatial Congruity	5	The sequestration factor was developed for waste from a North Carolina community; spatial variability is expected to be moderate to high.	10	States use state-level activity data to estimate state-wide emissions.	0.50
Temporal Congruity	5	The laboratory research was intended to simulate long-term degradation of organic wastes in a landfill; temporal variability is expected to be moderate to high.	10	States use activity data for a given year to estimate carbon sequestration associated with that year.	0.50
				Composite Score	**0.48**

TABLE 5.6-3

DARS SCORES: CO$_2$ EMISSIONS FROM WASTE COMBUSTION

DARS Attribute Category	Emission Factor Attribute	Explanation	Activity Data Attribute	Explanation	Emission Score
Measurement	5	The emission factor is based on an imprecise mass balance relationship.	10	The amount of waste combusted is measured by weighing garbage trucks before and after they tip their waste at the combustor.	0.50
Source Specificity	10	The emission factor was developed specifically for waste combustion.	9	The amount of waste combusted is very closely correlated to the emissions process.	0.90
Spatial Congruity	7	The emission factor is based on U.S. data, but the content of nonbiogenic carbon in waste varies depending on its source. Spatial variability is expected to be moderate.	10	States use state-level activity data to estimate state-wide emissions.	0.70
Temporal Congruity	7	The emission factor is based on mass balance, not on measured emissions over a particular time frame. The variability of the emission factor is expected to be low to moderate.	10	States use annual activity data to estimate annual emissions.	0.70
				Composite Score	**0.70**

TABLE 5.6-4

DARS SCORES: N$_2$O EMISSIONS FROM WASTE COMBUSTION

DARS Attribute Category	Emission Factor Attribute	Explanation	Activity Data Attribute	Explanation	Emission Score
Measurement	3	The emission factor was derived by averaging widely-varying measurements made throughout the world.	10	The amount of waste combusted is generally measured accurately by weighing garbage trucks before and after they tip their waste at the combustor.	0.30
Source Specificity	10	The emission factor was developed specifically for waste combustion.	6	The amount of waste combusted is correlated to the emissions process.	0.60
Spatial Congruity	5	The emission factor is based on global, not U.S., data; moreover, the emission level depends on the nature of the waste combusted.	10	States use state-level activity data to estimate state-wide emissions.	0.50
Temporal Congruity	9	The emission factor is based on an average of short-term measurements, not on year-long measurements. However, the emission factor is not believed to vary significantly over the course of a year.	10	States use annual activity data to estimate annual emissions.	0.90
				Composite Score	**0.58**

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